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PYROELECTRIC SURFACE ACOUSTIC WAVE SCANNED IMAGER ANALYSIS AND --ETC(U)

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by

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Research Department

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One method of circumventing the cooling problem is to use the pyroelectrical effect for the infrared light sensing mechanism. When heated by incident radiation a pyroelectric develops a polarization surface charge. This polarization surface charge can exert an electric field on an adjacent semiconductor and change the charge distribution at its surface. If two SAWs in the pyroelectric interact nonlinearly with the varying surface charge in the semiconductor, then one can read out an image by observing the current versus time across the semiconductor.

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FOREWORD

This report covers information on pyroelectric imaging using SAW scanning. The results are applicable to other methods of image scanning as well.

This research was performed by the Naval Weapons Center during the period October 1976 to October 1977 and was supported by the Naval Air Systems Command under Task No. WF54584601.

This report has been prepared primarily for timely presentation of information and is released at the working level.

F. C. Essig
Head, Physics Division
Research Department
1 February 1978

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CONTENTS

INTRODUCTION

The possibility of using surface acoustic waves (SAWs) to scan optical images on semiconductors was demonstrated by Quate at Stanford University in 1972. In order to do the analogous scanning of images in the infrared portion of the spectrum one has to cool the semiconductor to about 100 K. This increases initial system cost, decreases shelf life span, and requires additional servicing when operationally deployed.

One method of circumventing the cooling problem is to use the pyroelectrical effect for the infrared light sensing mechanism. When heated by incident radiation a pyroelectric develops a polarization surface charge. This polarization surface charge can exert an electric field on an adjacent semiconductor and change the charge distribution at its surface. If two SAWs in the pyroelectric interact nonlinearly with the varying surface charge in the semiconductor, then one can read out an image by observing the current versus time across the semiconductor.

DISCUSSION

Several pyroelectric SAW scanned imagers ($LiTaO_3$ on silicon) were constructed and tested using a 1000°C blackbody source chopped at various rates. These imagers were tested with and without a germanium window to absorb the radiation of photons of energy above the band gap of silicon. The test setup is shown in Figure 1.

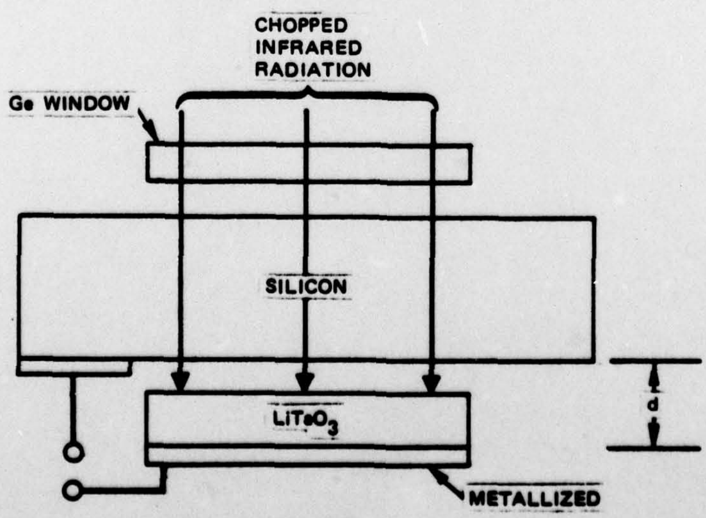

FIGURE 1. Experimental Arrangement.

For the chopping rates used, the silicon is like a perfect conductor forming the upper plate of the capacitor of plate spacing d. A potential difference between the plates is developed by heating the $LiTaO_3$ by infrared radiation. $LiTaO_3$ is a pyroelectric of moderate pyroelectric coefficient.

Radiation of wavelengths longer than 2.0 µm is transmitted by the silicon and is absorbed at the surface of the $LiTaO_3$. Heat then diffuses into the $LiTaO_3$, changing its temperature, and thus induces a spontaneous polarization surface charge on the $LiTaO_3$.

The germanium-filtered blackbody irradiance at the device was measured to be 0.028 W/cm^2 using a Scientech thermopile. Now the blackbody slide rule shows that 0.006 W/cm^2 can be absorbed in the $LiTaO_3$ while only 50% of this is transmitted by the silicon. This leaves 0.003 W/cm^2 absorbed at the Si-$LiTaO_3$ interface.

Appendix A shows that the expected potential difference between the $LiTaO_3$ electrode and the silicon (when this is not short-circuited) is given by

$$\Delta V = \frac{\Delta V_o A/B}{(1 + A/B)} = \frac{p\Delta H\ A/B}{\varepsilon C_v (1 + A/B)\omega} \tag{1}$$

where

ΔV = potential difference
p = pyroelectric coefficient = 17×10^{-5} C m^{-2}-K^{-1}
ΔH = irradiance variation = 30 W m^{-2}
A = illuminated area
B = unilluminated area } $A/B = 0.20$
ε = dielectric constant = 3.9×10^{-10} F m^{-1}
C_v = heat capacity = 3.2×10^6 J m^{-3} K^{-1}
ω = chopper angular rate = 10 rad/s.

Thus,

$$\Delta V = 0.070 \text{ V} \tag{2}$$

Using an electrometer to avoid voltage drop across the device, this potential difference was measured to be 0.055 V. The difference is probably due to heat loss by conduction into the adjacent silicon.

When the silicon and lower electrode of the $LiTaO_3$ are shorted together and the device is uniformly illuminated (shown in Appendix B), the external electric field incident on the silicon is given by

6

$$E_{ext} = \frac{\varepsilon}{\varepsilon_o} \frac{\Delta V_o}{d} \tag{3}$$

where the parameters which have not been previously defined are

ε_o = permittivity of vacuum = 8.9×10^{-12} F m^{-1}
d = thickness of $LiTaO_3$ = 0.001 m.

The result is

$$E_{ext} = 18060 \text{ V/m} \tag{4}$$

When the semiconductor is at or near zero temperature, the charge density versus depth into the semiconductor is as shown in Figure 1, where the depth to which the charge extends is just sufficient to cancel the external field and is called the depleted depth. In this limit, the depleted depth, ΔW_o, is related to external field by

$$\Delta W_o = \frac{\varepsilon_o \Delta E_{ext}}{qN_d} \tag{5}$$

where

ΔE_{ext} = pyroelectrically generated field = 18060 V/m
ε_o = dielectric constant of vacuum = 9×10^{-12} F m^{-1}
q = electronic charge = 1.6×10^{-19} C
N_D = donor density = 10^{21} m^{-3}

thus

$$\Delta W_o = 1.0 \times 10^{-9} \text{ m}$$

For finite temperatures the edge of the depleted regions is not sharp, as shown in Figure 2. The charge density in the semiconductor is given by Sze (Eq. 9.9).[1]

$$\rho = -q[n_{no}(e^{\beta\psi} - 1) - p_{no}(e^{-\beta\psi} - 1)] \tag{6}$$

where ψ is a potential to be determined by the differential equation

$$E = -\frac{d\psi}{dx} = \frac{2}{\beta}\left(\frac{qn_{no}\beta}{\varepsilon}\right)^{1/2}\left[(e^{-\beta\psi} - \beta\psi - 1) + \frac{p_{no}}{n_{no}}(e^{-\beta\psi} + \beta\psi - 1)\right]^{1/2} \tag{7}$$

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[1] S. M. Sze. *Physics of Semiconductor Devices*. John Wiley and Sons, New York, N.Y. (1969).

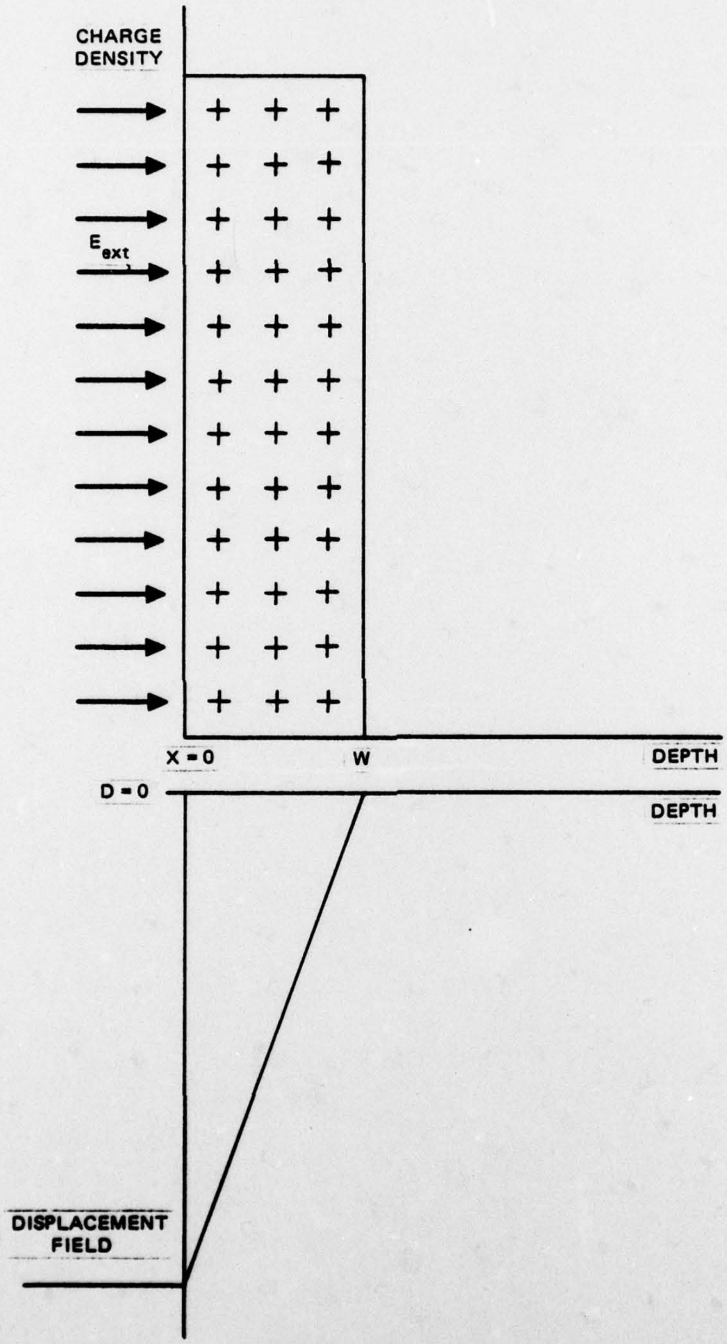

FIGURE 2. Zero Temperature Charge Density and Displacement Field.

8

where

$$\beta = q/kT$$
$$n_{no} = N_D$$
$$p_{no}n_{no} = n_i^2$$
k = Boltzmann's constant
T = absolute temperature
n_i = intrinsic charge density = $10^{16}/m^3$ at T = 300 K

The term ψ at x=0 is determined by setting the field E equal to $E_s = E_{ext}/\varepsilon_s$, where ε_s is the dielectric constant of the semiconductor, and iteratively solving Eq. (7) for ψ. Having obtained E_s and ψ_s, one simply solves Eq. (7) for $\psi(x)$ by iterating x in sufficiently small increments.

Having obtained $\psi(x)$ one may use Eq. (6) to obtain $\rho(x)$ versus x. This is shown in Figure 3 for several values of pyroelectric temperature. With larger external fields, such as at $E=E_4$, we obtain complete depletion (800 C/m^3) at the surface and a shape which approximates that of Figure 2 but with rounding at the edge of the depleted zone.

The important thing to note from Figure 3 is that, even with the rounding, the change in depth where half depletion occurs is approximately the same as it would be if calculated from Eq. (5) for a given external field change.

Appendix C shows that the ratio of the irradiance emanating from a chopped 1000°C source near 300 K, and relative to a source 1 K hotter than the chopper blades, is 3.46×10^4 for the 6-15 µm region to which $LiTaO_3$ is sensitive. This implies that the depletion depth change is 10^{-9} m/3.46×10^4 = 2.9×10^{-14} m for the scene temperature variation of about 1 K. Our sensitivity expectations[2] using visible light on silicon are 0.01 Lux or 1.4×10^{-11} W/cm^2 which corresponds to a depletion depth change

$$\Delta W = \frac{H\tau}{h\nu N_d} = \frac{(1.4 \times 10^{-11}\ W/cm^2)(0.033\ s)}{(2.0 \times 10^{-19}\ J)\ 10^{15}/cm^3}$$

$$\Delta W = 2.3 \times 10^{-9}\ cm = 2.3 \times 10^{-11}\ m \qquad (8)$$

[2]H. P. Leet. "Surface Acoustic Wave IR Scan Device Technology: Image Sensor Application to Navy Air." Written for program sponsor. Copies obtainable from author at Naval Weapons Center, China Lake, California 93555.

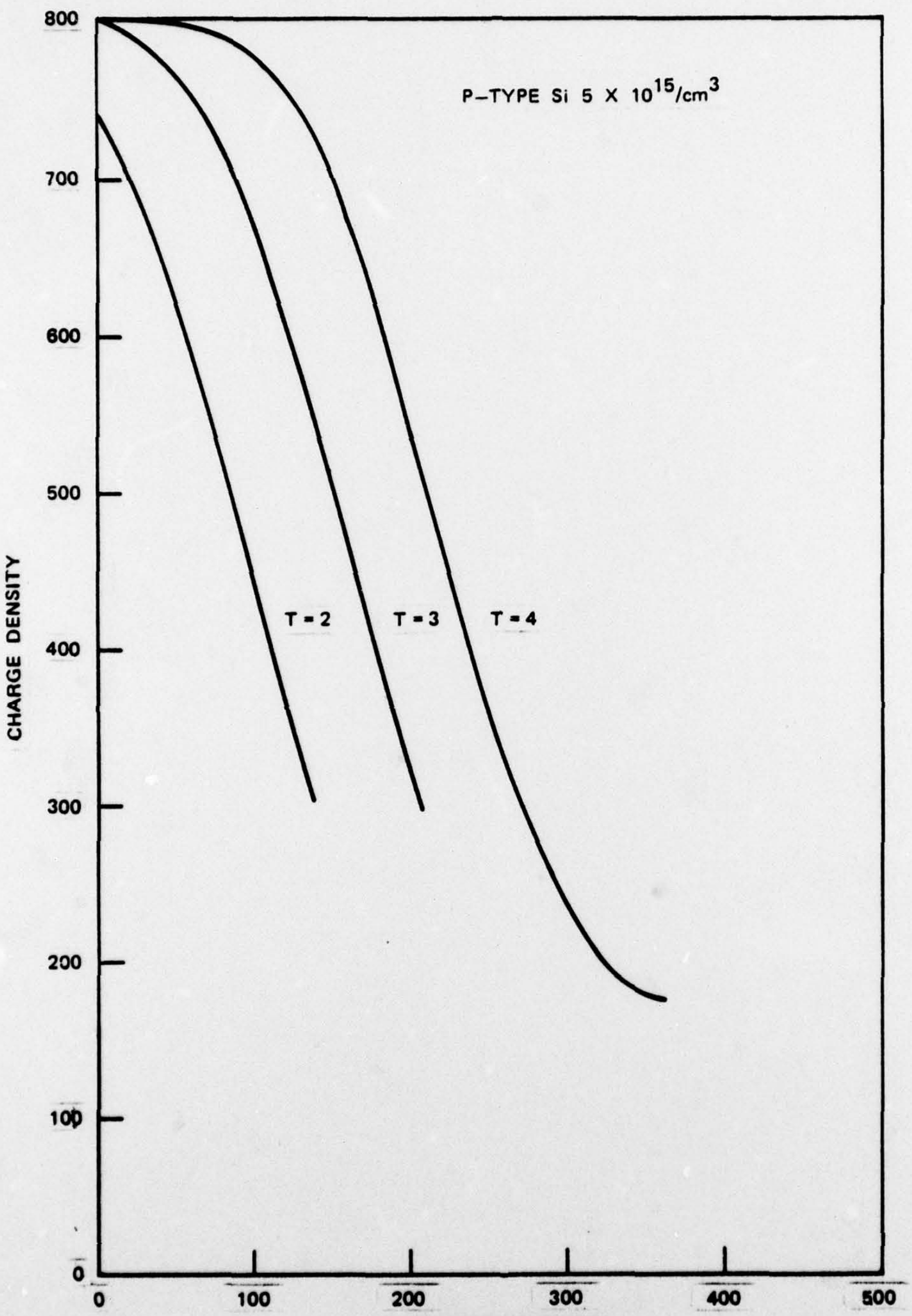

FIGURE 3. Room Temperature Charge Density.

10

where

τ = integration time = 0.033 s
H = noise equivalent irradiance = 1.4×10^{-11} W/cm^2
hν = photon energy = 2×10^{-19} J
N_d = donor density = 10^{15}/cm^3

Thus, for the pyroelectric device, the analysis shows that, even with the most sensitive configuration using silicon diodes as the semiconductor medium, we are three orders of magnitude from sensing a thermal scene and could just barely expect to sense a 1000°C scene.

The low effective quantum efficiency of a good pyroelectric was recognized more than a year ago by the author. However, there existed the possibility of some phenomenon other than depletion-depth-change-due-to-pyroelectric-charge. However, experimental investigations show no SAW attenuation or phase velocity change due to even a chopped 1000°C source focused directly onto the pyroelectric using an f/2 lens. The literature[3] confuses the analysis with equations like

$$-\nabla \cdot E = (\nabla \cdot P_s - \rho_o)/\varepsilon \tag{9}$$

where ρ_o is the free charge density, P_s the spontaneous polarization, and E the electric field.

The correct form is

$$-\nabla \cdot E = (\nabla \cdot P_s - \rho_o)/\varepsilon_o \tag{10}$$

In the results of Ref. 3 this error is corrected by reinterpretation of the pyroelectric coefficient. The correct interpretation is given in Appendix D.

It is of interest to consider the temperature changes at the surface of $LiTaO_3$ when chopped, focused light of a scene 1 K hotter or colder than the chopper blades impinges on the surface. In Appendix E, this case is considered for a chopping rate of 167 Hz, which allows equilibration of the temperature variations throughout the thickness of the assumed 30-μm-thick detector [i.e., $(D/\omega)^{1/2}$ = 30 μm where D is the diffusion coefficient, and $\omega = 2\pi(167)$]. Note that at this chopping rate the detector temperature variations are four orders of magnitude less than the scene temperature variations.

In light of these findings, the author feels that no further effort to implement a SAW scanned pyroelectric device is warranted unless new, more favorable, geometries or materials become available.

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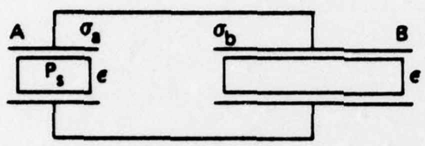
[3] B. Turner and H. A. H. Boot. "The Thermo Imaging Response of a Pyroelectric Target," *Infrared Physics*, Vol. 16 (May 1975), pp. 367-374.

Appendix A

POTENTIAL DIFFERENCE BETWEEN PLATES OF A PYROELECTRIC DETECTOR ASSUMING NON-UNIFORM ILLUMINATION



$$\sigma_a A = -\sigma_b B \text{ (charge conservation)}$$

$$V_b = V_a = \frac{\sigma_b d}{\varepsilon} = -\frac{\sigma_a A d}{B\varepsilon}$$

$$V_a = \frac{\sigma_a d}{\varepsilon} - \Delta V_o$$

where ΔV_o is given by Eq. (19) of Ref. 3;

$$\Delta V_o = \frac{p\Delta H}{\varepsilon C_v \omega}$$

thus

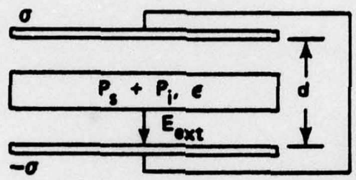
$$\frac{\sigma_a d}{\varepsilon} = \frac{\Delta V_o}{d(1 + A/B)}$$

then

$$V_b = \frac{A/B\ \Delta V_o}{(1 + A/B)}$$

Appendix B

CALCULATION OF EXTERNAL ELECTRIC FIELD FOR A UNIFORMLY ILLUMINATED PYROELECTRIC DECTOR



If the pyroelectric material fills the space between the plates

$$\sigma/\varepsilon d - \Delta V_o = 0$$

$$\sigma = \varepsilon \Delta V/d$$

$$E_{ext} = \sigma/\varepsilon_o = \varepsilon/\varepsilon_o(\Delta V_o/d)$$

13

Appendix C

CALCULATION OF RATIO OF IRRADIANCE OF A 1000°C SOURCE RELATIVE TO A 1°C ABOVE ROOM TEMPERATURE SOURCE

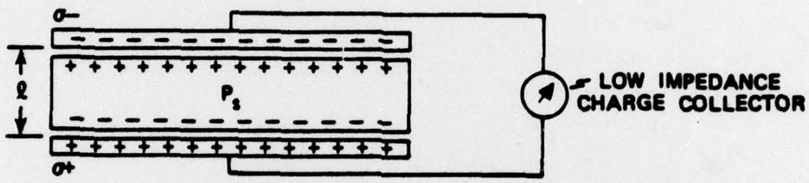
$$\underset{6\text{-}15\ \mu m}{\Delta H\ (1000°C)} / \underset{6\text{-}15\ \mu m}{\Delta H\ (\Delta 1°C)}$$

$$\Delta H(301\text{-}300) = 7.4 \times 10^{-5}\ W/cm^2\text{-}K$$

$$\frac{\Delta H\ (1000)}{\Delta H\ (300)} = \frac{2.56}{7.4 \times 10^{-5}\ W/cm^2} = 3.46 \times 10^4$$

Appendix D

MEANING OF p: THE PYROELECTRIC COEFFICIENT



$$Pi + \varepsilon_o Ei = \varepsilon Ei = \sigma$$

$$E_s = -P_s/\varepsilon_o$$

$$\Delta V = (\sigma/\varepsilon - P_1/\varepsilon_o)\ell$$

If charge flows into the charge collector such that the voltage across the device goes to zero then

$$\sigma/\varepsilon = P_s/\varepsilon_o \quad \text{or} \quad \sigma = P_s \varepsilon/\varepsilon_o = p\Delta T$$

It is σ and <u>not</u> P_s which is the surface charge density per unit area generated by a 1 K change in temperature.

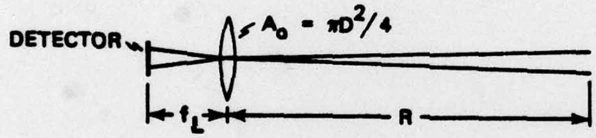
Thus, $P_s = \varepsilon_o/\varepsilon \; p\Delta T$

Appendix E

CALCULATION OF INDUCED DETECTOR TEMPERATURE VARIATION FOR A GIVEN SCENE VARIATION

Here we make a calculation of $\Delta T_D/\Delta T_s$ where ΔT_s is the scene temperature variation and ΔT_D is the detector temperature variation at its front face.

$$\frac{dP_D}{dT_s} = \frac{A_o}{R^2} H_s A_t = A_o H_s \Omega t \tag{E-1}$$



where A_o is the area of the optics, H_s is the scene power output/(cm^2-sr-°K) and A_t is the area of the target. Then the irradiance variation at the detector front face is

$$\frac{\Delta H_D}{\Delta T_s} = \frac{A_o H_s}{f_L^{\ 2}} \tag{E-2}$$

where f_L is the focal length of the optics and ΔH_D is the irradiance change on the detector. But $A_o/f_L^{\ 2} = \pi(\mathrm{NA})^2$ where NA is the numerical aperture.

Thus, $H_D = (\mathrm{NA})^2 \pi H_s$; using Holeman and Wreathall's expression for low spatial frequency and thin detectors[4]

$$\frac{\Delta T_D}{\Delta T_s} = \frac{\pi(\mathrm{NA})^2 H_s}{C_v \omega b} \tag{E-3}$$

where

$b = 30\ \mu m = 0.003$ cm = detector thickness

$H_s = 7.4 \times 10^{-5}$ W/cm^2-K

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[4]B. R. Holeman and W. M. Wreathall. "Thermal Imaging Camera Tubes with Pyroelectric Targets," *J Phys D: Appl Phys*, Vol. 4 (1971).

C_v = 3.2 J/cm^3-K = heat capacity/unit volume

ω = $2\pi(167)$ = chopping angular frequency

NA = 1

then

$$\frac{\Delta T_D}{\Delta T_s} = \frac{\pi(1)(7.4 \times 10^{-5})}{3.2(2\pi)(167)(0.003)} = 2.3 \times 10^{-5} \qquad \text{(E-4)}$$

One may note that the second law of thermodynamics disallows the possibility of $\Delta T_D/\Delta T_s > 1$ and we did not take into consideration heat losses due to reradiation here.